# Detection of the Molecular Oxygen Isotopomer $^{16}O^{18}O$ in Interstellar Clouds

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## Abstract

We report the first detection of molecular oxygen in interstellar clouds by observation of the 234 GHz $(N,J) = (2,1) - (0,1)$ line of the isotopomer $^{16}O^{18}O$ towards NGC 7538. The line has a peak intensity of $8 \pm 1.7$ mK and an integrated intensity of $10 \pm 1.5$ mK km s$^{-1}$. The corresponding $C^{18}O$ line is peaked near the position of the $^{16}O^{18}O$ detection and has a linewidth roughly four times larger. The ratio of $^{16}O^{18}O/C^{18}O$ is 3 if we restrict the $C^{18}O$ column density to the $^{16}O^{18}O$ linewidth, and 0.8 using the entire $C^{18}O$ line. The corresponding $O_2/CO$ ratio implies that the ratio of gaseous carbon to oxygen is about 0.35 to 0.7 within the range usually assumed in chemical models. We also observed several cold dark clouds (L134N, B5, TMC2) and but without success; our upper limits for these sources are significantly below those reported previously. The best limit is for B5 and TMC2 where $O_2/CO$ is below 0.23 (at the 3 $\sigma$ level). This is the first report of upper limits that are actually below the standard $O_2/CO$ ratio.

## 1. Introduction

Oxygen is the most abundant heavy element in the Galaxy and in its various forms is one of the most important species in the chemistry and energy balance of interstellar clouds. In the dense molecular clouds, gas phase oxygen is predicted to be mostly in CO, $O_2$, and $H_2O$; however, only CO is readily observable and, despite their importance, it has been very difficult to study $O_2$ and $H_2O$ in clouds. Both molecules are not directly observable from the ground because of their large presence in the Earth's atmosphere and only the rarer isotopomers can be observed with ground-based telescopes. In the case of molecular oxygen the situation is even worse than for $H_2O$ because its rotational lines arise from a magnetic dipole coupling and have very small Einstein A coefficients (c.f. Black and Smith 1984). These make the detection of $^{16}O^{16}O$ and $^{16}O^{18}O$ very difficult. One of the lines of $^{16}O^{18}O$, the $(N,J) = (2,1) - (0,1)$ transition at 233.946 GHz, can be observed with ground-based telescopes providing that the line is Doppler-shifted enough not to fall within the telluric line. For $^{16}O^{16}O$ it is necessary to observe highly redshifted external galaxies to avoid the mesospheric lines and the sensitivity of these searches are further limited by beam resolution, especially if the oxygen emission is confined to small cores (unlike CO in external galaxies which is more widespread). For $^{16}O^{18}O$ Black and Smith (1984) predict brightness temperatures typically two orders of magnitude below $C^{18}O$ under the same column density and excitation conditions. Thus only very sensitive observations could have a chance of detecting $^{18}O^{16}O$ and all previous attempts have failed for lack of sufficient sensitivity (Goldsmith 1985; Liszt 1985; Combes, 1991; Bergman, 1993). Though these authors report limits on the $O_2/CO$ ratio as low as 0.2, we found that after correcting in some cases for more realistic $C^{18}O$ column densities and by consistently estimating all the upper limits as 3 times the rms deviation of a channel the same width as the FWHM of the $C^{18}O$ line, that the best limit on the $^{16}O^{18}O/C^{18}O$ ratio is no more than 0.85 (in $\rho$ Oph A). Thus some of the previous limits might have to be lowered by as much as a factor of two. Thus we suggest that no previous search reached an upper limit low enough to contradict the standard gas phase chemical models, which predict a C/O ratio of 0.2 - 0.4, where C/O < 1 and most of the C locked up in CO.

The installation of a new, sensitive SIS receiver on the POM-2 mini-millimeter telescope (Castets, 1988) combined with large amounts of observing time gave us an opportunity to attempt a new detection of the $^{16}O^{18}O$ at 234 GHz. We report here the detection of the 234 GHz line of $^{16}O^{18}O$ in NGC 7538 and significant $O_2/CO$ upper limits towards a number of sources.

## 2. Observations

The observations were made in several runs at the POM-2 telescope. A first unsuccessful attempt was made in February 1992 and after some improvements in the receiver three more weeks were devoted to this search in December 1992 and January 1993. The POM-2 instrument has been much improved since its original installation mainly by replacing the Schottky diode mixer with an SIS mixer of temperature $T_{rec}$ (DSB) = 85 ± 10 K and by improving the coupling of the receiver to the antenna (forward and beam efficiencies have been increased by 12%, reaching $\eta_f = 0.82$ and $\eta_{fs} = 0.68$). The system temperature varied between 500 and 1200 K as a function of elevation and the water vapor content varied between 0.5 and 3 mm of precipitable water during the observing runs. Pointing was checked on Jupiter and in $^{12}CO$ on IRC+10216. The absolute pointing error is less than 30 arcsec and the rms tracking error less than 15 arcsec. The beam size is 140 arcsec FWHM at 234 GHz.

The observations were made with the autocorrelator backend in the high resolution mode (18 MHz bandwidth, 78 kHz = 0.1 km s$^{-1}$ resolution) using frequency switching with a shift of 14 MHz. This switching allows us to discriminate against possible image sideband lines which

would appear negative in the difference signal. However the baseline is not as good as in the beam switching mode (which is not available on POM-2). Calibration was done every 10 minutes and the intermediate frequency was switched between two values 1 MHz apart every other scan (= 5 minutes) in order to detect parasitic lines. Every three hours or so, the intermediate frequency was displaced to a new value in a range between 1530 and 1560 MHz to smooth out any weak parasitic lines too small to appear on a single scan. The image frequency is in a region slightly above the $^{12}CO$ (J = 2-1) transition where no line has been seen in the Orion A survey of Sutton (1985).

The frequency tuning was checked by observing the atmospheric $^{16}O^{18}O$ emission which is easily detected. The receiver was calibrated and the sky temperature measured against hot and cold loads. A major source of uncertainty is the sideband gain ratio which is known to be somewhat variable on SIS receivers. It may yield an underestimate of the line intensity as large as 30 to 40 percent in $^{12}CO$. The $^{16}O^{18}O$ values given here are not corrected for this possible defect. The $C^{18}O$ spectra, observed in the lower sideband do not suffer from it and are thus correctly calibrated.

After folding the spectra, a third order polynomial baseline was subtracted. Most of the spectra did not show any parasitic lines, however we also checked that the sporadic parasitic lines, which appeared from time to time, added no noticeable contribution at the frequency of interest. To do this we compared the raw data all summed together (with many different intermediate frequencies) with the sum of all spectra which had individual rms noise below some limit (after clipping some conspicuous parasitic lines or eliminating the worst spectra). The results are essentially identical and the final rms noise was only slightly improved in the purged and clipped version of the spectra.

3. Results and Discussion

The sources we observed are listed in Table 1 along with their positions, and the line parameters or limits for $^{16}O^{18}O$ and $C^{18}O$. We detected a clear signal at the 234 GHz $^{16}O^{18}O$ line in only one of the sources, NGC 7538 (Fig. 1) and only upper limits towards the others: L134N, B5 (Fig. 2) and TMC 2. As discussed below, we believe that the line in NGC 7538 is most likely the long sought interstellar isotopomer oxygen. In Table 2 we indicate the $C^{18}O$ column densities for each source derived using an LVG model assuming spherical symmetry. In the case of $^{16}O^{18}O$ we calculate (using a LTE model and assuming the gas to be optically thin) the column density for NGC 7538 and the upper limits for the other sources based on the noise over a channel the width of the $C^{18}O$ line (FWHM). Finally, we list the $^{16}O^{18}O/C^{18}O$ ratio using the usual assumption $^{16}O^{16}O = 250$ $^{16}O^{18}O$ (see below).

The line in NGC 7538 is clearly visible. The integrated intensity, $10 \pm 1.5$ mK km s$^{-1}$ is a 7 sigma detection. The line peak LSR velocity is about -55.3 km s$^{-1}$ close to the $C^{18}O$ peak velocity, -56.1 km s$^{-1}$. We cannot exclude the detection of some mesospheric $O_3$ rare isotopomer as most of the observations of NGC 7538 were made within a two week period with only a small change in the Doppler-shift corrections; as no other source was observed at the same corrected frequency we cannot check for this possibility in other spectra. We expect to check this point by observing NGC 7538 at some other time.

The $C^{18}O$ (J = 1 - 0) and (J = 2 - 1) lines of NGC 7538 are interesting (Fig. 1) because a) they have a low and similar intensity, in contrast to CS (J = 2 - 1) $\approx$ 5 K, which is surprising for such a dense and warm source, and b) their shapes are clearly different from one another - the J = 2 - 1 line seems to have a dip at the $^{16}O^{18}O$ peak velocity. These two remarks may well indicate that

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$C^{18}O$ is optically thick in that source and more so at the $^{16}O^{18}O$ velocity. Also among many observations of other lines in NGC 7538 we note: the HDO detection at -58.8 and -59.9 km s$^{-1}$ (Jacq, 1990); the $^{13}CO$ peaks at -53 km s$^{-1}$ on the east side and -59 km s$^{-1}$ at the center, with a systemic complex velocity of -54 km s$^{-1}$ (Dickel, 1981; Campbell, 1984) and high resolution data obtained at OVRO show a rotating $^{13}CO$ disk peaking at -55.7 km s$^{-1}$ (Scoville, 1986) on the east side of the infrared sources. Finally, Pratap, 1989 find an HCN peak velocity at -56 km s$^{-1}$ and HCN clumps at -55.75 km s$^{-1}$ and they, along with Schilke (1991) find a peculiar $^{15}NH_3$ (3,3) maser emitting at -55.6 km s$^{-1}$. Thus there exist tracers of high density gas that have at some places, velocities corresponding to that of $^{16}O^{18}O$.

To estimate the $^{16}O^{18}O$ column densities, we assume that the lines are optically thin and that the levels are thermalized. This is very likely to be the case because in NGC 7538 because the source is relatively warm (40 K) and dense (even within the POM-2 beam), as indicated by our $C^{18}O$ (J = 1-0) and CS (J = 2-1) maps from Bell Labs and a CS (J = 5-4) observation from POM-2. The thermalization assumption might be might be more questionable in the cold sources or if the emission arises from the envelope of NGC 7538. In any case the lines should be optically thin which means that the LTE assumption gives more conservative upper limits for this ground transition. The column density is given by,

$$N(^{16}O^{18}O) = 1.16 \times 10^{17} \, f(T_{kin}) \, (T_{kin} - 5.5) \, [1 - \exp(-h\nu/kT_{kin})]^{-1} \, \int(\delta T_r^* \, dv) \quad (cm^{-2}) \qquad (1)$$

where $f(T_{kin})$ is the fraction of the population in the (N,J) = (0,1) level at temperature $T_{kin}$, $\delta T_r^*$ is the antenna excess temperature over the 2.7 K background. The other terms have their usual meaning and the integral is over the total linewidth.

If we consider that the limited velocity range of the $^{16}O^{18}O$ is linked to a particular emitting region then we have to consider separately the relative abundance of $^{16}O^{18}O$ with respect to that velocity interval and we can only set an upper limit for the remaining velocity range traced by the $C^{18}O$. The ratio of $N(^{16}O^{18}O)/N(C^{18}O)$ is 2.9 if we restrict the $C^{18}O$ column density to the $^{16}O^{18}O$ linewidth, and 0.8 using the entire $C^{18}O$ line. However, if the $C^{18}O$ line is optically thick at the velocity of the $^{16}O^{18}O$ as suggested by the $C^{18}O$ (J = 2-1) line profile, the former ratio is only an upper limit. In the cold clouds the best limit is towards B5 and TMC 2 which have $N(^{16}O^{18}O)/N(C^{18}O)$ below 0.46 and 0.4, respectively assuming the $C^{18}O$ lines to be optically thin.

There have been numerous models of the chemistry of oxygen in interstellar clouds and all of them generally predict substantial abundances of molecular oxygen in dark, dense shielded regions, provided that the gas phase ratio of carbon to oxygen is less than one, as would be expected from the cosmic abundances. Only one of the models actually treats the oxygen 16 and 18 isotopic species separately (Langer et al. 1984) and these authors found that the $^{16}O/^{18}O$ "fractionation" did not exceed 12 percent for single ratios. There are only two major channels for forming $O_2$, O + NO and O + OH. However, because $^{16}O^{18}O$ can be produced by two pathways, for example, $^{16}O + ^{18}OH$ and $^{18}O + ^{16}OH$, as opposed to only one for $^{16}O^{16}O$, it is likely that $N(^{16}O^{16}O) = 0.5 \times (^{16}O/^{18}O) \, N(^{16}O^{18}O)$. Indeed most authors have adopted this conversion (see Liszt 1985) and scale the $N(^{16}O^{18}O)$ by 250 to obtain $N(^{16}O^{16}O)$.

Since the early model results of Langer et al. there have been a number of changes in the chemistry due to better laboratory measurements, mainly the finding that $H_3O^+$ + e recombines mostly to OH. Furthermore, the $H_3^+$ + e recombination has now been shown to be rapid (as was

assumed in the paper by Graedel, Langer, and Frerking 1982 and Langer et al. (1984); but not Langer and Graedel (1989). For that reason we will use the earlier calculations for abundance comparisons. These do not differ significantly from most models, which are anyway uncertain to some degree. An approximate solution of the steady state chemistry of molecular oxygen can be easily constructed, as has recently been done by Liszt (1992). In the standard model $O_2$ is produced by the reactions of O + OH and NO (NO itself is a product of N + OH), and OH is produced by a reaction chain beginning with $H_3^+$ + O. The $O_2$ is destroyed primarily by ion reactions with $He^+$ and $C^+$ neutral reactions with atomic carbon, and cosmic ray produced photons. Therefore to produce a large $O_2$ abundance requires that the electron abundance be low, thus increasing the $H_3^+$, and that the neutral carbon abundance be low. If the ions destroy $O_2$, and carbon is mainly in CO (assuming C/O < 1) then the fractional abundance of $O_2$ is,

$$X(O_2) \approx \alpha \, [\xi_O - \xi_C]/(1 + 2\,\alpha), \tag{2}$$

where $\xi_O$ and $\xi_C$ are the oxygen and carbon elemental abundances and $\alpha \approx 8/[1 + 10\,X_{-6}(e)]$ with $X_{-6}(e)$ in units of $10^{-6}$, being the degree of ionization. Thus to have 20 percent or more of the oxygen in $O_2$ requires $X(e) < 10^{-6}$. If neutral carbon is abundant in dense regions (either because it is out of equilibrium or UV is present) then

$$X(O_2) \approx \alpha \, [\xi_O - \xi_{CO}]/(1 + 2\,\alpha), \tag{3}$$

and $\alpha \approx [\zeta_{-17}/n_4]/[\xi_{-4}(O)X_{-6}(C)]$, where $\zeta_{-17}$ is the cosmic ray ionization rate in units of $10^{-17}$ s$^{-1}$ per H atom, $n_4$ the hydrogen density and $\xi_{-4}(O)$ the elemental abundance of oxygen. Large amounts of $O_2$ will be present only if $X(C) < 10^{-6}$. Thus in dense shielded regions we expect $X(O_2)/X(CO) \approx (0.2 - 0.4)$ - see for example the solutions in Langer, 1984.

Our results in NGC 7538 for $N(^{16}O^{18}O)/N(C^{18}O)$ imply a ratio of $N(^{16}O_2)/N(CO) > 0.4$, and << 1.5 which is compatible with chemical model predictions for C/O cosmic ratio 0.4 - 0.5. The upper limits in the other clouds, $N(^{16}O_2)/N(CO) < 0.2$ to 0.4, are still consistent with chemical models. Thus a deeper search for $^{16}O^{18}O$ is needed and observations of neutral carbon are important for all the sources.

4. Conclusion

We report the first detection of $^{16}O^{18}O$ in an interstellar cloud, NGC 7538, and we have improved the best upper limits in other sources by a factor of several. We were able to accomplish these results by using a very low noise receiver and dedicating a lot of observing time to a few sources. This shows the difficulty in studying molecular oxygen from ground based facilities. Our results indicate that the $^{16}O^{18}O$ region in NGC 7538 has a high molecular oxygen abundance. The corresponding $O_2/CO$ ratio implies that the fractional abundance of gaseous oxygen, $3 \times 10^{-4} >> X(O_2) > 0.5 \times 10^{-4}$, and is not as depleted as has previously been assumed in some chemical models. Observations of other lines of $^{16}O^{18}O$ (e.g. 298.4 and 401.7 GHz) are needed to confirm our detection and to check the $O_2/CO$ ratio.

## REFERENCES

Bergman, P., Hjalmarson, A., Booth, R., and Mattila, K., 1993, A&A, submitted.

Black, J. H. and Smith, P. I. 1984, Ap J. 277, 562.

Campbell, B. and Thompson, R. I., 1984, Ap J. 279, 650.

Castets, A., Lucas, R., and Lazareff, B., et al., 1988, A&A 194, 340.

Combes, F., Casoli, F., Encrenaz, P., Gerin, M., and Laurent, C., 1991, A&A 248, 607.

Dickel, H. R., Dickel, J. R., and Wilson, W. J., 1981, Ap. J., 250, L43.1981

Goldsmith, P. F., Snell, R. L., and Erickson, N. R. et al., 1985, ApJ 289, 613.

Graedel, T. E., Langer, W. D., and Frerking, M. A., 1982, Ap J. Supp. 48, 321.

Jacq, T., Walmsley, C. M., Henkel, C., et al. 1990, A&A 228, 447.

Kutner, M. L. and Ulich, B. L., 1981, Ap. J., 250, 341.

Langer, W. D., Graedel, T. E., Frerking, M. A., and Armentrout, P. B., 1984, Ap. J., 277, 581.

Langer, W. D. and Graedel, T. E. 1989, Ap. J. Supp., 69, 241.

Liszt, H. S., 1992, Ap. J., 386, 139.

Liszt, H. S. and Vanden Bout, P. A., 1985, Ap. J., 291, 178.

Pratap, P., Batrla, W., and Snyder, L. E., 1989, Ap. J., 341, 832.

Scoville, N. Z., Sargent, A. I., Sanders, D. B., et al., 1986, Ap. J., 303,416.

Schilke, P., Walmsley, C. M., and Mauersberger, R., 1991, A&A, 247, 516.

Sutton,E. C., Blake, G. A., Masson, C. R., and Phillips, T. G., 1985, Ap. J. Suppl., 58, 341.

**Table 1.** Source List and Observational Results.

| Source | Reference | Position | $T_r*(K)$ $C^{18}O$ | $T_r*(K)$ $C^{18}O$ | $C^{18}O$ $\delta v$ | $^{16}O^{18}O$ $\int T_r\, dv$ |
|---|---|---|---|---|---|---|
| | R.A. (1950) | Dec. (1950) | (J = 1-0) | (J = 2-1) | (km s$^{-1}$) | (mK km s$^{-1}$) |
| B5 | $3^h44^m29^s$ | $32°44'30''$ | 2.45 | 1.3 | 0.8 | $\leq 13$ |
| TMC2 | $4^h29^m43^s$ | $24°16''55''$ | 2.25 | 1.6 | 0.8 | $\leq 10$ |
| L134N | $15^h51^m30^s$ | $-2°43'36''$ | 2.2 | 1.5 | 0.5 | $\leq 14$ |
| NGC 7538 | $23^h11^m38^s$ | $61°10''48''$ | 0.9 | 1.2 | 4.4 | $13 \pm 2$ |

Upper limits are given as 3 times the rms deviation of a channel the width of the $C^{18}O$ line. In NGC 7538, the $^{16}O^{18}O$ FWHM line is 1.2 km s$^{-1}$ and the 1 $\sigma$ deviation is given for the integral. $C^{18}O$ data are from Bell Labs (J = 1-0) and POM-2 (J = 2-1).

**Table 2.** Column Densities and Abundance Ratios

| Source | $N(C^{18}O)^a$ cm$^{-2}$ | $N(^{16}O^{18}O)$ cm$^{-2}$ | $[^{16}O^{18}O/C^{16}O]^b$ |
|---|---|---|---|
| B5 | 2.2E15 | $\leq 1.3E15$ | $\leq 0.29$ |
| TMC2 | 2.0E15 | $\leq 1E15$ | $\leq 0.27$ |
| L134N | 1.2E15 | $\leq 1.4E15$ | $\leq 0.58$ |
| NGC 7538$^c$ | 1.0E15 3.9E15 | 3.25E15 | 0.4 1.6 |

a. An LVG model is used for $C^{18}O$ while LTE is assumed for molecular oxygen (see text).
b. The estimates of the $O_2/CO$ ratio assume $^{16}O^{16}O/^{16}O^{18}O$ equal to 250.
c. Two figures are given for C18O depending on whether we consider the full $C^{18}O$ width or the $^{16}O^{18}O$ width apply to the determination of $C^{18}O$ column density (see text).

**Figure Captions**

Fig. 1a.  NGC 7538 $C^{18}O$ (J = 2->1), and $^{16}O^{18}O$ (N,J) = (2,1) -> (0,1) lines.  Horizontal axis is the LSR Velocity (km s-1) and vertical axis is the corrected radiation temperature $T_r^*$ as defined by Kutner and Ulich (1981).  The Oxygen line has been scaled by 50.

Fig. 1b.  NGC 7538 $C^{18}O$ (J = 1->0) line.  Horizontal axis is the LSR Velocity (km s-1) and vertical axis is the corrected radiation temperature $T_r^*$.

Fig. 2.  B5 $C^{18}O$ (J=2->1) and $^{16}O^{18}O$ (N,J) = (2,1) -> (0,1) lines.  The Oxygen spectrum has been scaled by 10.

NGC 7538

$C^{18}O$ $(J : 2 \rightarrow 1)$

$^{16}O^{18}O \times 50$

Velocity (km/s)

$(T_0)$
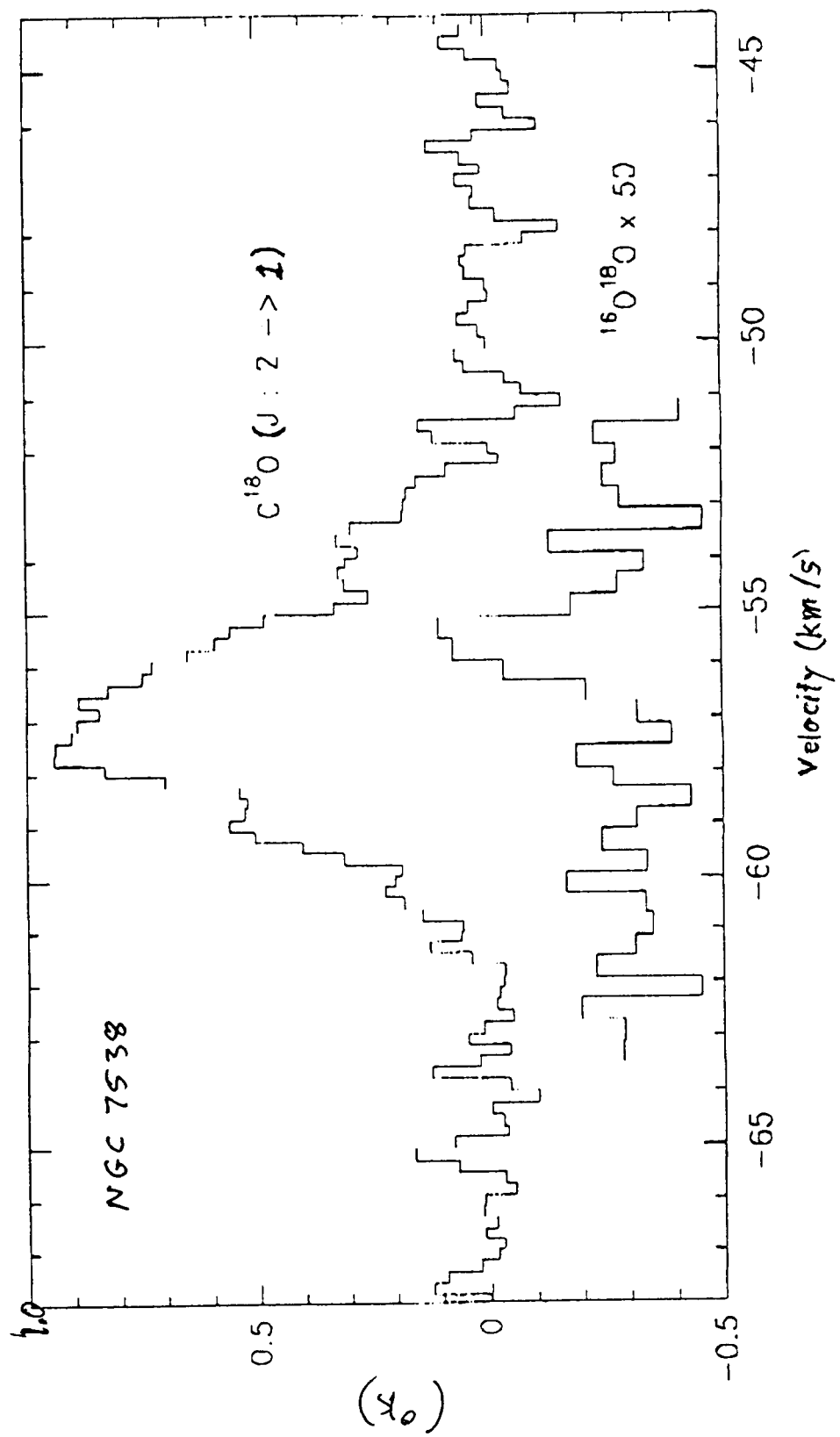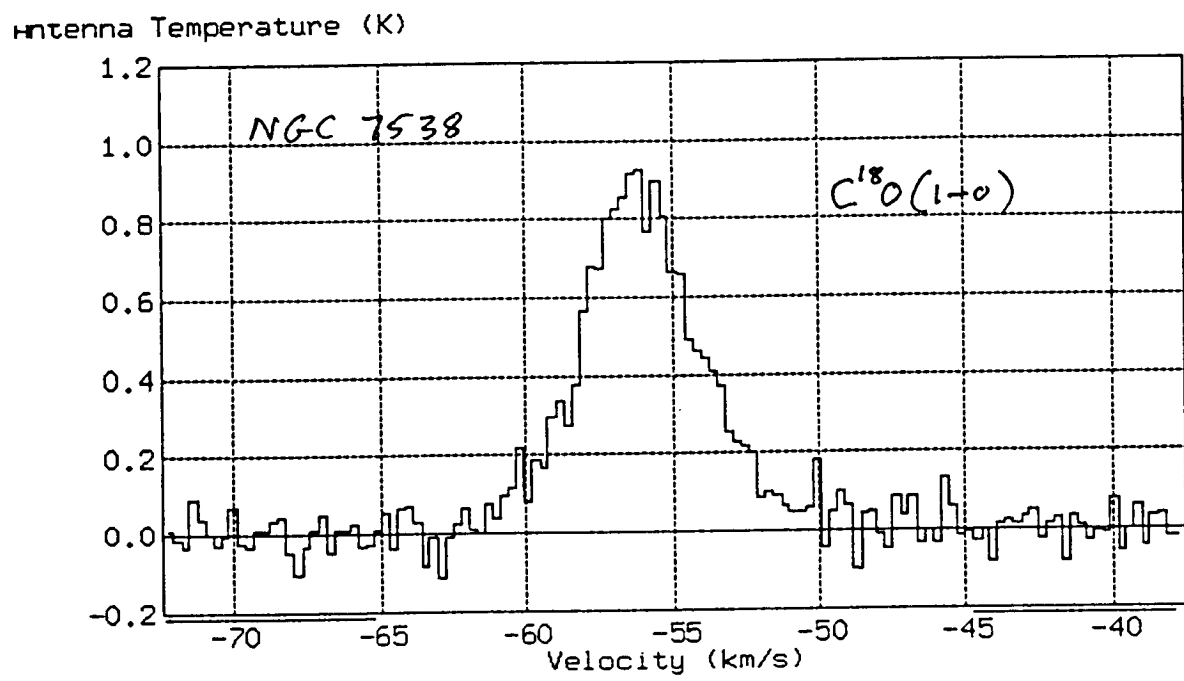
Figure 1a

Figure 16.

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$C^{18}O \ (J : 2 \to 1)$

$^{15}C^{18}O \times 10$

velocity (km/s)

$(T_o)$

Fig 2